

Could Spontaneous Transitions be Spontaneous?¹

Bernd A. Berg^{2,3}

Abstract

It is considered to re-formulate quantum theory as it appears: A theory of continuous and causal time evolution, interrupted by discontinuous and stochastic jumps. Relying on a global reduction process, a hypothesis is introduced postulating spontaneous collapse of superpositions of states which describe spontaneous absorption or emission. The collapse probability determines a mean collapse time $\tau^c = b\hbar/\Delta E$, where b is a dimensionless constant and ΔE is the difference in energy distribution between alternative branches. Ramsey atomic beam spectroscopy yields a lower bound on b and avalanche photodiodes give an upper bound, such that $1.35 \cdot 10^{11} < b < 3.8 \cdot 10^{21}$.

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²Department of Physics, The Florida State University, Tallahassee, FL 32306, USA.

³Supercomputer Computations Research Institute, Tallahassee, FL 32306, USA.

⁴E-mail: berg@hep.fsu.edu; Fax: (850) 644 6735.

A photographic plate consists of an emulsion which separates grains of AgCl (or similar) molecules. Let me present a simplified discussion of the detection of a single photon. The photon may dissociate an AgCl molecule. The Cl escapes, whereas the Ag radical starts, upon photographic development, a chemical reaction which leaves a small, visible spot. Before detection the one-particle photon wave may pass through *both* parts of a double slit, see for instance ref.[1]. The geometry of the device (distance between the slits etc.) can be chosen such that the photon is spread out over a region covering distances much larger than a single grain, which determines the size of the finally visible spot. The physics which causes the photon wave to collapse is not understood.

Let us first recall where the Schrödinger equation leaves us. For simplicity we assume that each grain consists of precisely one AgCl molecule. We label the AgCl molecules on the plate by $i = 1, \dots, n$ and assume that the relevant features of the photographic plate are described by products of AgCl molecule wave functions. Initially the state is

$$|\Psi\rangle = |\Psi_0\rangle = \prod_{i=1}^n |\psi_i^b\rangle, \quad \langle\Psi_0|\Psi_0\rangle = 1, \quad (1)$$

where the $|\psi_i^b\rangle$, ($i = 1, \dots, n$) indicate the *bound* AgCl molecules and the overlap between different molecules is neglected, *i.e.* $\langle\psi_i^b|\psi_j^b\rangle = \delta_{ij}$. Through interaction with the photon the state is transformed into

$$|\Psi\rangle = c_0|\Psi_0\rangle + \sum_{j=1}^n c_j|\Psi_j\rangle \quad \text{with} \quad |\Psi_j\rangle = |\psi_j^d\rangle \prod_{i \neq j} |\psi_i^b\rangle, \quad \langle\Psi_j|\Psi_j\rangle = 1. \quad (2)$$

Here $|\psi_j^d\rangle$, ($j = 1, \dots, n$) denotes a *dissociated* AgCl molecule. A quantum measurement is constituted by the fact that only one of the $|\Psi_j\rangle$, ($j = 0, 1, \dots, n$) states survives, each with probability $P_j = |c_j|^2$, $\sum_{j=0}^n P_j = 1$. The probabilities P_j are related to the photon wave function ψ_{ph} by means of

$$P_j = \text{const} \int_{V_j} d^3x |\psi_{ph}|^2, \quad j = 1, \dots, n. \quad (3)$$

The constant does not depend on j , and V_j is a cross-sectional volume corresponding to the j th molecule. Picking a branch $|\Psi_j\rangle$ becomes in this way interpreted as observing the photon at the position V_j (for a perfect detector $c_0 = 0$). It is remarkable that in this process of measurement the photon becomes destroyed through spontaneous absorption by the dissociating molecule. To summarize, measurements perform wave function *reductions* by making decisions between alternatives proposed by the continuous, causal time evolution part of Quantum Theory (QT). In our example the reduction decides the location of the visible spot. Given the photon wave function ψ_{ph} , QT predicts probabilities for the reduction alternatives.

Whereas time evolution from eqn.(1) to (2) is described by the Schrödinger equation, this is not true (or at least controversial) for the measurement process. Decoherence theory, for an overview see [2], tries to establish that conventional time evolution leads, in the situation

of eqn.(2), to $\langle \Psi_j | \Psi_k \rangle = 0$ for $j \neq k$, such that it becomes impossible to observe contradictions with interference effects predicted by the Schrödinger equation. In contrast to this, explicit collapse models predict deviations from conventional QT, see for instance [3]. So far, no such deviations have been measured. The Schrödinger equation, more precisely its applicable relativistic generalization $|\Psi(t)\rangle = \exp(-Ht) |\Psi(0)\rangle$, describes a continuous and causal time evolution and I shall use the notation Quantum Object (QO) for matter $|\Psi(t)\rangle$ as long as it exhibits this behavior. Concerning the measurement process, it seems to be widely believed that many body processes, involving $\gg 10^{10}$ particles [1], are responsible. In the presented example the photographic plate, possibly also the environment beyond, would be blamed. However, the ultimate collapse into one branch $|\Psi_j\rangle$ remains an unexplained property. No satisfactory derivation from the known properties of microscopic matter appears possible. Consequently, a search for hereto overlooked new, fundamental properties of matter is legitimate.

The question arose whether hidden variables may exist which ensure local, continuous and causal time development for the entire system, including measurements. Bell [4] turned this apparently philosophical question into physics by showing that all such local, realistic theories are measurably distinct from QT (Bell's inequalities). Subsequently, many experiments were performed and local, realistic theories are now convincingly excluded. For instance, the experiments of [6] found violations of Bell's inequalities for spacelike measurements on entangled quantum states. In such experiments one performs measurements at distinct locations, say \vec{x}_1 and \vec{x}_2 , in time intervals small enough that any mutual influence through communication at or below the speed of light can be excluded. Results at \vec{x}_1 correlate with those at \vec{x}_2 (and vice versa) in a way that *excludes* an interpretation as a classical correlation, see [5] for a pedagogical presentation. Such effects underline the need for qualitatively new properties of matter, because they cannot be propagated through local, relativistic wave equations (which also govern the interaction with the environment).

Also a consistent description of the space-time evolution of the quantum state vector $|\Psi\rangle$ under such measurements encounters difficulties. After accepting that a measurement at (ct_1, \vec{x}_1) or (ct_2, \vec{x}_2) interrupts the continuous, causal time evolution by a discontinuous jump, one faces the problem that Lorentz transformations can change the time ordering of spacelike events. In a recent paper [7] it has been shown that a spacetime picture for a physical state vector with relativistically covariant reduction exists. It may be summarized as follows:

- (1) Measurement are performed by detectors, which are part of the state vector, at localized spacetime positions (ct_i, \vec{x}_i) , $i = 1, 2, \dots$
- (2) Discontinuous reductions of the state vector are defined on certain Lorentz covariant spacelike hypersurfaces, which in some neighbourhood of a detector include its backward light cone.
- (3) The thus defined measurements happen in some reduction order, which is *not* a time

ordering with respect to a particular inertial frame.

Based on this scenario, I pursue in the present paper an approach which builds on the strengths of QT and tries to supplement it with new laws for reductions, such that the conventional rules for measurements (Born's probability interpretation) follow. These laws are supposed to act on the *microscopic* level, independently of whether macroscopic measurements are actually carried out or not. Typically, they will effect some interference phenomena. This implies observable consequences and makes their eventual existence a physical issue. On the other hand, we will see that rules can be designed in a way that most interference effects survive entirely, whereas those affected are only weakened in the sense of a decreased signal over background ratio (visibility). That makes such laws difficult to detect, as most experiments work with ensembles of particles and are happy to demonstrate a small signal over a large (subtracted) background. Fortunately, recent years have seen considerable improvements of experimental techniques, such that invoking experimental input may become feasible.

The central idea of my approach is to *propose* that the Ability To Perform Reductions (ATPR) between alternatives proposed by QT is a hereto unidentified *elementary* property of microscopic matter. I shall use the notation Quantum Detector (QD) to denote microscopic as well as macroscopic matter acting in its ATPR. Matter gets such a dual character: As QO it follows the continuous, deterministic time evolution. As QD it has the ATPR and causes jumps in the wave function. The goal is to explain the functioning of actually existing macroscopic detectors from the properties of microscopic QDs. Within our hypothetical framework central questions are now:

- (1) Which conglomerates of matter constitute a QD?
- (2) Which are precisely the alternatives of QT standing up for reductions?
- (3) What are the rules according to which QDs make their reductions?

It is unlikely, that ultimate answers can be found without additional experimental guidance. But it is instructive to introduce a simple hypothesis which allows (a) to illustrate the possibilities and general direction of the approach and (b) focuses on questions about experimental input which, quite generally, may be crucial for achieving progress in the field.

Let us return to the detection of a photon by a photographic plate. The simplest possibility is to attribute to each *single* AgCl molecule the ATPR about collapsing the photon wave function. As this is a spontaneous absorption, we get to the question asked in the title of this paper. We assume that each molecule acts independently when making its reductions and, by chance, the j^{th} molecule makes its reduction first, ahead of the others. The alternative is to decay or to stay intact. Either choice causes a jump in the wave function $|\Psi\rangle$ of eqn.(2). Subsequently rules are given which seem (a) to be minimal and (b) consistent with observations.

The collapse results are fixed by the rules of quantum mechanics. Namely, to be either (f stands for final)

$$|\Psi\rangle \rightarrow |\Psi\rangle_f = \frac{c_j}{\sqrt{P_j}} |\Psi_j\rangle \quad \text{with probability } P_j = |c_j|^2 \quad (4)$$

or

$$|\Psi\rangle \rightarrow |\Psi'\rangle = \sum_{k \neq j} c'_k |\Psi_k\rangle, \quad c'_k = \frac{c_k}{\sqrt{1 - P_j}}, \quad \text{with probability } 1 - P_j. \quad (5)$$

The k -sum in eqn.(5) includes $k = 0$, compare (2). The particular choice of the phase factors, $c_j/\sqrt{P_j}$ and $c_k/\sqrt{1 - P_j}$, assumes that a decoherence process leads into alternative branches, whereas for collapse with incomplete decoherence the issue would have to be resolved by the collapse rules. Each molecule thus constitutes a QD. As their mutual distances are short and their relative motion is negligible, compared to the speed of light, we can ignore the relativistic complications discussed in [7] (the backward light-cone becomes an excellent approximation to “instantaneous”).

Equation (4) implies as final result a dark spot at the position of molecule j . By construction this happens with the correct probability P_j . As soon as the wave function (4) rules, the reduction is completed. This is different when molecule j stays intact. Then the same rules (4) and (5), which collapse $|\Psi\rangle$ of eqn.(2), have now to be applied to the wave function $|\Psi'\rangle$ of eqn.(5). Assume, molecule l (note $l \neq j$ as the branch $|\Psi_j\rangle$ does no longer exist) makes the next reduction. The transformation will be either

$$|\Psi'\rangle \rightarrow |\Psi\rangle_f = \frac{c'_l}{\sqrt{P'_l}} |\Psi_l\rangle \quad \text{with probability } P'_l = |c'_l|^2 \quad (6)$$

or

$$|\Psi'\rangle \rightarrow |\Psi''\rangle = \sum_{k \neq j, l} c''_k |\Psi_k\rangle, \quad c''_k = \frac{c'_k}{\sqrt{1 - P'_l}}, \quad \text{with probability } 1 - P'_l.$$

Putting equations (5) and (6) together, we obtain

$$|\Psi\rangle \rightarrow |\Psi\rangle_f = \frac{c_l}{\sqrt{P_l}} |\Psi_l\rangle \quad \text{with probability } P_l,$$

i.e. precisely the correct likelihood to find the dark spot at the position of molecule l . Continuing the procedure, it is easy to see that all probabilities come out right.

Once a molecule j , $j = 1, \dots, n$ has collapsed $|\Psi\rangle$ into the $|\Psi\rangle_f$ state of eqn.(4), the chemical reaction¹ – initiated by the corresponding branch of each molecule – survives only in the neighbourhood of molecule j , where the visible spot will occur. Let $t = 0$ be the time at which the photon hits the photographic plate. This time is well-defined as long as we can assume that the photon flight time over a distance of the relevant thickness of the

¹During the chemical reaction similar collapse processes may continue. Presently, they are not of interest to us, as our aim is to discuss the collapse of the incoming photon wave function, which has the special property of being transversally spread out over a macroscopic region.

photographic plate (for example $0.3 \text{ mm} \Rightarrow \Delta t = 10^{-12} \text{ s} = 1 \text{ ps}$) is much smaller than the typical collapse time. Let us denote by

$$P^f(t) = (1 - P_0) (1 - e^{-t/\tau^f(t)}) \quad (7)$$

the probability that, at time t , the (entire) system has decided about the location of the dark spot. Here $P_0 = |c_0|^2$, see eqn.(2), is the probability that the system fails to detect. The r.h.s. of (7) defines the system collapse time $\tau^f(t)$. If τ^f is constant, it is the mean time the system needs to make its reduction (with corresponding collapse probability density $(\tau^f)^{-1} \exp(-t/\tau^f)$).

Let us assume that each molecule performs reductions on its own and that $\rho_j^c(t)$ is the likelihood per time unit that the j^{th} molecule makes its reduction. We simplify the situation further and consider a $\rho_j^c(t)$ that does not depend on j and is a step function: $\rho_j^c(t) = \rho^c \theta(t)$ with $\rho^c = \text{constant}$. The corresponding one molecule collapse probability is

$$p^c(t) = (1 - e^{-t/\tau^c}) \theta(t), \quad (8)$$

where $\tau^c = 1/\rho^c$ is the mean collapse time of a single molecule. The molecules make their reductions in some sequential order. For our purposes the reductions process comes to a halt as soon as one molecule has decayed. Assume, $n^c(t)$ molecules made their reductions. Whatever values the P_j in eqn.(4) take, $P^f(t) = (n^c(t)/n) (1 - P_0)$ is the probability that the collapse process has selected a definite location. As $n^c(t) = n p^c(t)$, we conclude

$$P^f(t) = (1 - P_0) p^c(t). \quad (9)$$

With the approximations made the system collapse time τ^f , defined by (7), and the single molecule collapse time τ^c , defined by (8), are identical. Soon some arguments will be given that the constant τ^c should be regarded as upper bound of the system collapse time $\tau^f(t)$.

Let us return to the central questions. In our discussion of detection of a spread-out photon, I assumed the following: (1) Each, single AgCl molecule may act as QD. (2) One alternative stands up for reduction: decaying (through absorbing the photon) or staying intact. (3) Each AgCl makes its reduction with a certain, constant likelihood per time unit: ρ^c .

Ad (1): Assuming that a single AgCl molecule can act as QD reflects the attempt to introduce an ATPR as a fundamental property of microscopic matter. In our simplified discussion each AgCl molecule is separated from the others by the emulsion and causal interactions between them can be neglected. In a real photographic film only grains of AgCl molecules are separated. Causal interactions between an AgCl molecule and its neighbors within one grain cannot be neglected. Indeed, the initiated chemical process will spread out over the entire grain. If the collapse time is sufficiently large, competing (ultimately alternative) chemical processes would start to evolve in several grains. Under such circumstances, the definition of the QD should be extended to include each causally connected region of AgCl molecules. As a general rule, I find it attractive to conjecture that a conglomerate

of matter which (in a reasonable approximation) can be treated as isolated QO can also be regarded as isolated QD. Neglecting the influence of most of the world is precisely how we get solutions out of QT. The hypothesis is, whenever this works well for a QO, this QO may also constitute a QD whose reduction probabilities are determined by its local quantum state, although this quantum state may participate in discontinuous, non-local transformations.

Ad (2): The scenario, pursued now, is that the QT alternatives up for reductions have, quite generally, to do with absorption and emission of particles. Here I limit the discussion to the absorption and emission of photons, the process argued to be at the heart of every real, existing and functioning measurement device. Of course, other physical processes (like for instance in nuclear decay) should then be governed by similar rules. In essence: Ruled by not yet identified *stochastic* laws, superpositions of Fock space sectors with distinct particle numbers are conjectured to collapse into particle number eigenstate sectors.

Ad (3): Our ATPR introduces an explicit arrow in time. This is attractive, because it is a matter of fact that such an arrow exists. The canonical conjugate variable to time is energy. Therefore, a frequency law which relates the collapse time to the difference ΔE in energy distribution between emerging branches is suggested

$$\tau^c = \tau^c(\Delta E), \quad (10)$$

where the energy difference is defined as the one experienced by the QD. For example, in case of our single AgCl molecule the difference between absorbing or not absorbing the photon is: $\Delta E = E_\gamma$, where E_γ is the energy of the photon. The total energy is (in the same way as in QT) conserved in our approach.

The introduced system has been chosen because of its popularity in QT text books in connection with the double slit effect. Instead of the photographic plate other measurement devices can be considered. For instance, the emergence of a track in a bubble chamber through ionization by an high energy particle allows a similar discussion. Here it is instructive to consider the emergence of such a track in monatomic dilute gas, say hydrogen. Assume that *one* incoming high energy particle has been split into two distinct transversally sharp rays¹, each with 50% probability content. At time $t = 0$ the two rays may hit spacelike regions of hydrogen gas. Each ray builds up a column of half-ionized atoms. Let us focus on one of them, consisting of n participating atoms. If one of the atoms of our column emits a photon by re-capturing an electron the relevant reduction has been made. A transformation of type (4) puts all atoms of the competing column into their unperturbed branches and the atoms of our column into their ionized branches. There is now some ambiguity about what should be considered a QD. Should each single atom (including the involved electrons) act as independent QD or should all atoms of the column together form one, single QD? In favor of the first viewpoint is that the gas is assumed to be dilute. Hence, the mutual influence through continuous, causal time evolution between the atoms is negligible. On the other

¹Within our approach it might, however, happen that such a state collapses spontaneously, because the device which caused the split (and hence correlates with it) might act as a QD.

hand, the high energy particle correlates all the atoms within the column (and, of course, also the other column): If one atom performs its reduction in favor of the ionized branch, all other are put there too. Assume the atoms act independently and the differences in energy distribution between their branches are ΔE_i , ($i = 1, \dots, n$), implying corresponding mean collapse times $\tau_i^c(\Delta E_i)$. The probability that none of them makes the reduction during the time interval $[0, t]$ becomes

$$q^c(t) = \prod_{i=1}^n \exp[-t/\tau_i^c(\Delta E_i)] = \exp\left[-\sum_{i=1}^n t/\tau_i^c(\Delta E_i)\right].$$

On the other hand, if they all together form one single QD, this probability becomes

$$q^c(t) = \exp[-t/\tau^c(\Delta E)], \quad \text{where} \quad \Delta E = \sum_{i=1}^n \Delta E_i$$

is the total difference in energy distribution between the alternative, macroscopic branches. Remarkably, the $q^c(t)$ of the last two equations agree, when the law for the mean collapse time is

$$\tau^c(\Delta E) = \frac{b \hbar}{\Delta E}, \quad (11)$$

where b is a dimensionless constant. (Correspondingly, $\tau_i^c = b \hbar / \Delta E_i$, $i = 1, \dots, n$, of course.) Equation (11) has phenomenologically attractive features. The first one is that the indicated ambiguity is rendered irrelevant. Another is that the collapse time becomes large for small energy differences. Especially, superpositions of states degenerate in energy will not collapse. In this context *a measurement device is now an apparatus which speeds up the collapse by increasing the difference in energy distribution between quantum branches*. Before the distinct branches become macroscopically visible, the energy difference becomes so large that collapse happens with (practical) certainty.

Are there observable consequences beyond standard QT? Reduction by an AgCl molecule destroys the possibility of interference of the branches (4) and (5) of the wave function (2). In particular, this does still hold for the case of a single molecule ($n = 1$). But it appears unlikely that anyone will, in the near future, measure interference effects between AgCl+ γ and Ag+Cl. Hence, there is no contradiction. In addition, it should be noted that our mechanism leaves the most commonly observed interference effects intact: Namely, all those which rely on the wave character of particles in a Fock space sector with fixed particle number. This includes photon or other particle waves passing through double slits and so on. Neutron interferometry which relies on hyperfine level splitting would, in principle, be suppressed. However, the energy differences are small such that observable effects are unlikely.

Larger energy differences are achieved in atomic beam spectroscopy. Ramsey fringes have been observed from interference of branches which differ by photon quanta with energy in the eV range. Figure 1 depicts the interaction geometry of Bordé [8], for a recent review see [9]. An atomic beam of two level systems ($E_0 < E_1$) interacts with two counterpropagating sets of a traveling laser wave. The laser frequency is tuned to the energy difference $\Delta E = E_1 - E_0$,

such that induced absorption/emission processes take place at each of the four interaction zones. The laser intensity is adjusted such that at each interaction zone an incoming partial wave is (further) split into two equally strong parts, $|\psi_0, m_0\rangle$ and $|\psi_1, m_1\rangle$. Here $|\psi_0\rangle$ denotes an atom in its incoming state, $|\psi_1\rangle$ an excited atom and m_0, m_1 are the numbers of photon moments transferred. Examples are indicated in the figure. The process leaves us with 2^n partial waves after the n^{th} interaction zone, $n = 1, 2, 3, 4$. Of the final sixteen partial waves $4 \cdot 2 = 8$ interfere under detuning of the laser frequency. Positions and directions of those eight partial waves are along the four lines, indicated after the last interaction zone of figure 1. The interference can be made visible by monitoring the decay luminosity I of the excited states $|\psi_1\rangle$ after the last interaction zone. The contrast or visibility is defined by

$$K = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (12)$$

where I_{\max} and I_{\min} are maximum and minimum of the measured luminosities. Eight of the final sixteen partial waves are in excited states and four of them interfere in two pairs, $|\psi_1, -1\rangle$ and $|\psi_1, 1\rangle$ of the figure. Hence, the optimal contrast for the Bordé geometry is

$$K_{\text{opt}} = \frac{(4 - 4) + (8 - 0)}{(4 + 4) + (8 + 0)} = 0.5. \quad (13)$$

This result is found by normalizing (in arbitrary units) the average luminosity of each excited partial wave to one. Four decoherent branches contribute then $I_{\max} = I_{\min} = 4$, whereas the other four excited partial waves contribute $I_{\min} = 0$ and $I_{\max} = 8$ (for I_{\min} they annihilate one another and in the other extreme they amplify).

According to our hypothesis, integer photon numbers get restored with a collapse time $\tau^c = \tau^c(\Delta E)$. If this happens in range 1 of figure 1, the interference effect becomes entirely destroyed. The likelihood for it to happen is $p^c = 1 - q^c$, where $q^c = \exp(-t_D/\tau^c)$ and t_D is the time an atom stays in range 1. In range 2 each of the two $|\psi_1, 1\rangle$ partial waves has borrowed $1/4$ of a photon from the laser beam. To get a unique collapse description, we invoke a minimality assumption: The splitting of the atom has to be constructed with the minimal number of photons possible. The assumption seems to be natural, because two photons with the same quantum numbers cannot be distinguished. It follows that the system can collapse either into the two $|\psi_1, 1\rangle$ partial waves or into the two $|\psi_0, 0\rangle$ partial waves. Neither collapse has observable consequences, because the interference effects of the upper part and lower part of figure 1 are not distinguished by measuring the decay luminosity. In range 3 two split photons (distinct momenta) get involved: One mediates collapse between $|\psi_1, 1\rangle$ and $|\psi_0, 2\rangle$, the other between $|\psi_0, 0\rangle$ and $|\psi_1, 1\rangle$. These two collapse processes are supposed to act independently. Each destroys, if it happens, half of the interference effect. The probability for both of them to happen is $(p^c)^2$ (using that t_D is identical in range 3 and 1) and the probability that one of them (excluding both) happens is $p^c = 1 - (q^c)^2 - (p^c)^2$. Putting things together, the optimal contrast becomes

$$K_{\text{opt}}^c = 16^{-1}[8 - 8p^c - 4q^c p^c - 8q^c (p^c)^2] = 0.5 \exp[-2t_D/\tau^c(\Delta E)]. \quad (14)$$

Experiments performed at the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig rely on the $^3P_1-^1S_0$ transition of ^{40}Ca which has $\lambda = 657.46 \text{ nm}$, *i.e.* $\Delta E = 1.886 \text{ eV}$. The best contrast achieved [10] is approximately $K = 0.2$ with $t_D = 21.6 \cdot 10^{-6} \text{ s}$. The actual experiments are performed using pulsed laser beams applied to laser cooled atoms in a magneto-optical trap. The times t_D and t_d , corresponding to the distances D and d of figure 1, are then the times between the laser pulses, see [9] for details. Relying on the PTB result we obtain the estimate

$$\tau_{\min}^c(1.89 \text{ eV}) = 2 t_D / \ln(5/2) = 47 \cdot 10^{-6} \text{ s} < \tau^c(1.89 \text{ eV})$$

which translates (11) into

$$b_{\min} = 1.35 \cdot 10^{11} < b. \quad (15)$$

That the constant b has to be large is no surprise, as the action $b\hbar$ marks the transition from quantum to classical physics. The bound (15) can easily be improved by estimating conventional effects which contribute to diminishing the contrast K . Beyond, a direct measurement of a non-zero τ^c requires that all other effects can convincingly be controlled and that still a gap between the estimated and measured contrast remains. Such an analysis goes beyond the scope of the present paper. Here, I am content with establishing firm, but crude, bounds on b .

Finally, in this paper, I derive an upper bound on b . Avalanche photodiodes are the up-to-date devices for achieving measurements in short time intervals, as needed for spacelike measurements [6]. Time resolutions down to 20 ps FWHM are achieved, see [11] for a recent review. The energy consumption is sharply peaked in these short intervals (order of watts), but does not translate into an immediate estimate of the collapse time. The reason is that collapse at some later time may lead to indistinguishable results. Claiming differently includes the task of disproving popular decoherence ideas [2]. Nevertheless, there is an easy way to estimate upper bounds by analysis of actually working measurement devices: Our approach makes only sense when the reduction process does keep up with the *sustained* performance of every real, existing measurement device. Then, the energy dissipation of such a device yields immediately an upper bound on b . Ref.[11] gives on p.1964 the example of a photo avalanche diode which operates at 10^5 cps and has a mean power dissipation of 4 mW . This translates into an energy consumption of about $2.5 \cdot 10^{11} \text{ eV}$ per count, *i.e.*

$$\tau^c(2.5 \cdot 10^{11} \text{ eV}) < \tau_{\max}^c(2.5 \cdot 10^{11} \text{ eV}) = 10^{-5} \text{ s},$$

which implies

$$b < b_{\max} = 3.8 \cdot 10^{21}. \quad (16)$$

Equation (15) and (16) leave a wide range open. An analysis of existing experiments should allow to narrow things down by at least a few orders of magnitude. Here the emphasis is on quoting safe, instead of sophisticated, bounds. Even this has caused some efforts, the reason simply being that experimentalists do not focus on the information needed.

In conclusion, we have discussed the possibility of attributing to microscopic matter the ability to perform wave function reductions. It is of interest to improve the bounds b_{\min} (15) and b_{\max} (16) for the collapse time $\tau^c(\Delta E)$ of equation (11). From this viewpoint, I would like to argue in favor of a paradigm shift concerning QT experiments. It is no longer of central interest to demonstrate the existence of one or another exotic interference effect. We know, they are there. Most interesting is to control that interference happens for every single, participating particle. This puts the focus on experiments with high visibility. If one could convincingly demonstrate that particles occasionally skip participation in an interference pattern, such a results could pave a major inroad towards understanding of the measurement process. The aim of pushing experiments towards optimal visibility is of interest in itself. Independent of its validity, the introduced collapse scenario provides an interesting classification pattern for such results: The achieved lower bounds b_{\min} should be compiled. Concerning b_{\max} , one is lead to minimizing the energy dissipation of measurement devices under sustained performance. Again, this is a goal of interest in itself.

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References

- [1] V.B. Braginsky and F.YA. Khalili, *Quantum Measurement*, Cambridge University Press, 1992.
- [2] W.H. Zurek, Prog. Theor. Phys. 80 (1993) 281; Physics Today 44(10) (1991) 36; D. Giulini et al., *Decoherence and the Appearance of a Classical World in Quantum Theory*, Springer, Berlin-Heidelberg, 1996.
- [3] G.C. Ghirardi, A. Rimini, and T. Weber, Phys. Rev. D34 (1986) 470; L. Diosi, Phys. Rev. A40 (1989) 1165; G.C. Ghirardi, P. Pearle, and A. Rimini, Phys. Rev. A42 (1990) 78; P. Pearle and E. Squires, Phys. Rev. Lett. 73 (1994) 1.
- [4] J.S. Bell, Physica 1 (1964) 195.
- [5] N.D. Mermin, Physics Today 38(4) (1985) 38; Am. J. Phys. 58 (1991) 731.
- [6] A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. 49 (1982) 1804; P.R. Tapster, J.G. Rarity and P.C.M. Owens, Phys. Rev. Lett. 73 (1994) 1923; W. Tittel, J. Brendel, B. Gisin, T. Herzog, H. Zbinden and N. Gisin, quant-ph/9707042.
- [7] B.A. Berg, *Relativistic Quantum Field Theory with a Physical State Vector*, quant-ph/9807046; see also quant-ph/9801003.
- [8] C.J. Bordé, Phys. Lett. A140 (1989) 10.

- [9] U. Sterr, K. Sengstock, W. Ertmer, F. Riehle and J. Helmcke, *Atom Interferometry Based on Separated Light Fields* in *Atom Interferometry*, P. Berman (editor), Academic Press, 1997, pp. 293-362.
- [10] F. Riehle, private correspondence.
- [11] S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa, *Appl. Optics* 35 (1996) 1956.

Figure Captions

Figure 1: Bordé interaction geometry [8, 9] of four traveling laser beams to create optical Ramsey fringes in atomic spectroscopy. The atomic beam is incoming from the left and (split in partial waves) outgoing to the right. Interactions zones are where the atomic beam crosses the vertical lines of the traveling laser beam. The numbers $i = 1, 2$ and 3 label free propagation ranges between the interaction zones. The numbers 0 and 4 label the free propagation ranges before the first and after the last interaction.

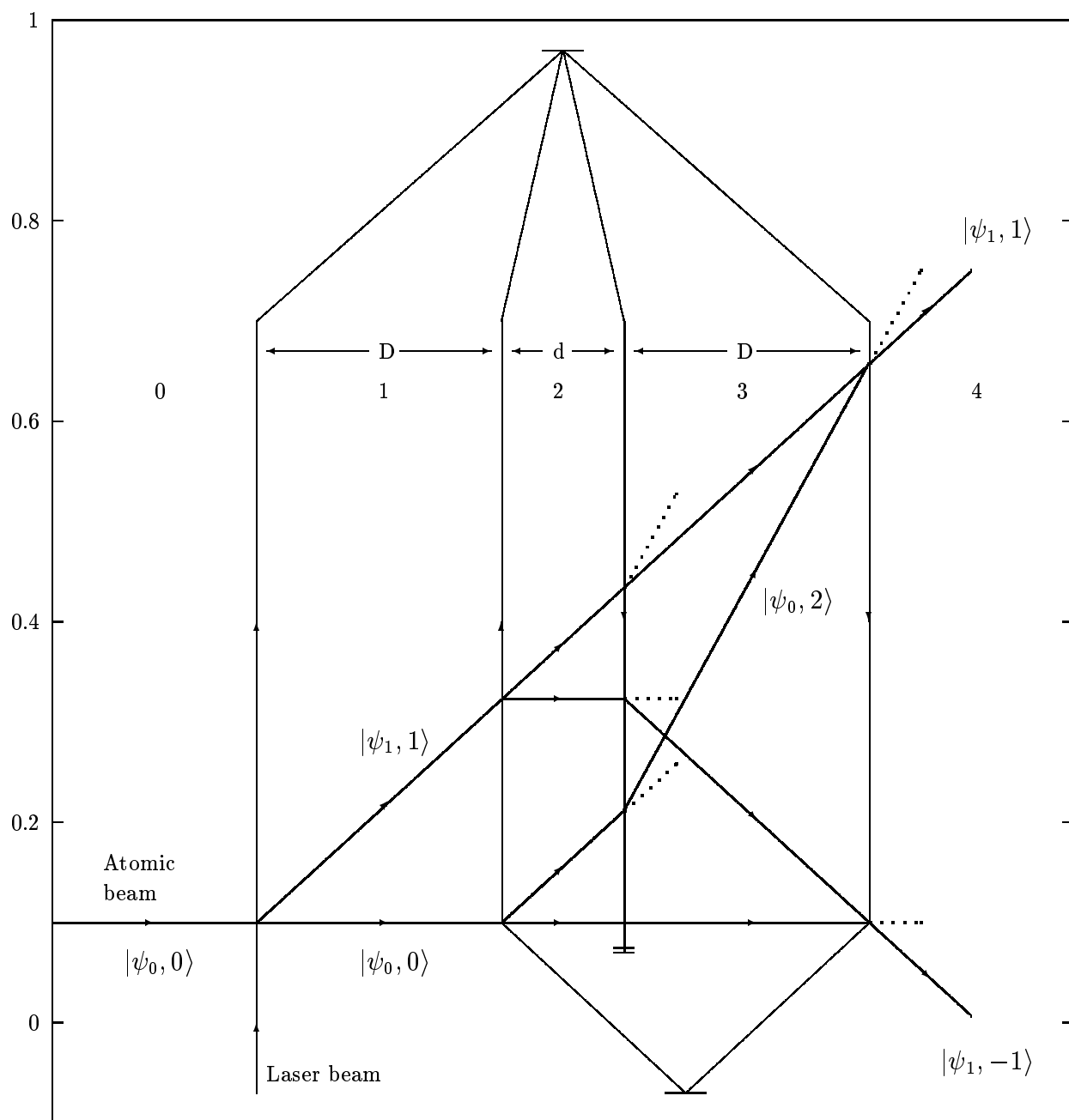


Figure 1